Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 61 (2014) 41 – 44

Energy Procedia

The 6th International Conference on Applied Energy – ICAE2014

A methodology for criticality analysis in symbiotic bioenergy parks

Michael Francis D. Benjamin[a,b], Raymond R. Tan[a,]*, Luis F. Razon[a]

[a]*Chemical Engineering Department*
Center for Engineering and Sustainable Development Research
De La Salle University, 2401 Taft Avenue, 1004 Manila, Philippines
[b]*Chemical Engineering Department*
University of Santo Tomas, España Blvd., 1006 Manila, Philippines

Abstract

The environmental performance of biomass processing plants can be enhanced through industrial symbiosis in bioenergy parks which utilize synergistic exchanges to ensure more sustainable operations. However, symbiosis will also increase the interdependence of plants, such that when one plant fails, there will be a cascading effect in the entire network. In this work, a criticality index is proposed to quantify the effects of a plant's failure to run at full capacity. This index is the ratio of the fractional change in the net output to the fractional change in capacity of the plant causing the failure. The plants in the entire bioenergy park can then be ranked based on this index. Such information can then be used for developing risk mitigation measures, such us planning for system redundancy. A case study is presented to demonstrate how the method determines the criticality of plants within a bioenergy park.

Peer-review under responsibility of the Organizing Committee of ICAE2014

Keywords: Bioenergy Parks, Industrial Symbiosis, Criticality Index.

1. Introduction

The production of biofuels is one of the key low-carbon technologies used to address the growing concerns on global energy security and climate change. Furthermore, environmental performance and efficiency of biomass processing plants can be enhanced through industrial symbiosis which results in bioenergy parks [1]. Such systems utilize synergistic product, by-product, and utility exchanges among the component plants to ensure more sustainable operations. Industrial symbiosis is a branch of industrial ecology that put together conventional stand-alone plants to cooperate for environmental gains [2].

* Corresponding author. Tel.: +632-536-4226; fax: +632-536-4226.
E-mail address: raymond.tan@dlsu.edu.ph.

Peer-review under responsibility of the Organizing Committee of ICAE2014
doi:10.1016/j.egypro.2014.11.901

However, due to the increased interdependence of component plants within a bioenergy park, there will be a cascading effect in the entire network when one plant becomes inoperable. Inoperability of one or more plants results in a deviation from an initial bioenergy park configuration. Cascading failure concepts are similar to those demonstrated in eco-industrial parks [3] and in multi-functional energy systems [4]. According to these works, the failure of a unit cascades that results into losses or possible collapse of the entire network. Thus, it is important to provide some criteria to evaluate the ability of a bioenergy park to withstand perturbations. Industrial networks can be modeled using Input-Output (IO) analysis [5,6]. IO models are used to quantify the robustness and risks associated with economic, environmental, and energy systems [7,8].

In this work, a criticality index is proposed to quantify the effects of a plant's failure within a bioenergy park. The plants in the entire bioenergy park can then be ranked based on this proposed index to determine which facilities are critical. Such information can then be used for developing risk mitigation measures, such us planning for system redundancy. A case study is presented to demonstrate the method.

2. Development of Criticality Index

For any given bioenergy park configuration, it is essential to have a quantitative means of assessing how the system topology creates dependencies among plants, and of assessing how vital each plant is to the network as a result of potential ripple effects of operational disruptions. This section discusses the procedure for the computation of a proposed criticality index for such systems. Each plant is described using only key mass or energy balances via Equation (1), where $\mathbf{A}$ is the *process matrix*, $\mathbf{x}$ is the *plant capacity vector*, and $\mathbf{y}$ is the *final output vector*. Then, a model for simultaneous exogenous specifications in the capacity and final output of a given system is used. The approach here is based on a method proposed for industrial networks [6] as shown by Equation (2). $\mathbf{A}'$ is the $k \times k$ matrix containing the elements from the first k rows and first k columns in matrix $\mathbf{A}$. $\mathbf{A}''$ is the $(n-k) \times k$ matrix in $\mathbf{A}$. $\mathbf{B}'$ is the $k \times (n-k)$ matrix in $(-\mathbf{A})$. $\mathbf{B}''$ is the $(n-k) \times (n-k)$ matrix in $(-\mathbf{A})$. Meanwhile, $\mathbf{x}'$ is k-element column vector containing endogenous capacity and $\mathbf{x}''$ is the $(n-k)$ element column vector with specified capacities, $\mathbf{y}'$ is the k-element column vector containing exogenously defined final outputs. Lastly, $\mathbf{y}''$ is the $(n-k)$ element column vector containing the endogenous final output streams.

$$\mathbf{Ax} = \mathbf{y} \tag{1}$$

$$\begin{bmatrix} \mathbf{0} & \mathbf{A}' \\ -\mathbf{I} & \mathbf{A}'' \end{bmatrix} \begin{bmatrix} \mathbf{y}'' \\ \mathbf{x}' \end{bmatrix} = \begin{bmatrix} \mathbf{B}' & \mathbf{I} \\ \mathbf{B}'' & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{x}'' \\ \mathbf{y}' \end{bmatrix} \tag{2}$$

$$\mathbf{c} = (\mathbf{y_o}'' - \mathbf{y_n}'')\,\hat{\mathbf{y}}_\mathbf{o}''^{-1} \tag{3}$$

$$\mathbf{z} = \mathbf{c}\,\hat{\mathbf{x}}_\mathbf{o}^{-1} \tag{4}$$

The final output of the affected product stream, $\mathbf{y}''$, can be solved using Equation (2). To compute for the criticality of each derated component plant in all scenarios, we define Equation (3). Where $\mathbf{c}$ is the *criticality column vector* containing the fractional change in the final output of the affected product streams relative to the baseline state. $\mathbf{y_o}''$ is the column vector containing the baseline demand of the final output streams, $\mathbf{y_n}''$ is the column vector containing the new final output of the product streams directly affected by the capacity reduction of component plants, and lastly, $\hat{\mathbf{y}}_\mathbf{o}''$ is a diagonal matrix containing the baseline demand of final output streams. Finally, the criticality index of all *nth* component plants is given by Equation (4). $\mathbf{z}$ is the *criticality index column vector* and $\hat{\mathbf{x}}_\mathbf{o}$ is the diagonal matrix containing the fractional change in component plant capacity causing the perturbation. A case study with different scenarios involving a symbiotic bioenergy park is presented next.

3. Case Study: Bioenergy Park

A hypothetical symbiotic bioenergy park shown in Figure 1 comprises the following component plants: Combined Heat and Power plant (CHP), Bioethanol plant (BEP), Biodiesel plant (BDP), and a Biogas Plant (BGP). These production plants are designed to produce the following main product streams: Power (P), Bioethanol (E), Biodiesel (D), and Biogas (G). It is assumed that each *nth* plant (e.g. CHP plant) produces a particular *nth* product (e.g. power) as its main output. The process matrix **A** consists of the first four data rows and first four data columns of Table 1. Equation (1) is used to solve the baseline capacities of the component plants, shown in Table 2, as well as the stream rates (i.e. product, by-product, and utility). Figure 1 shows the complete baseline state of the bioenergy park.

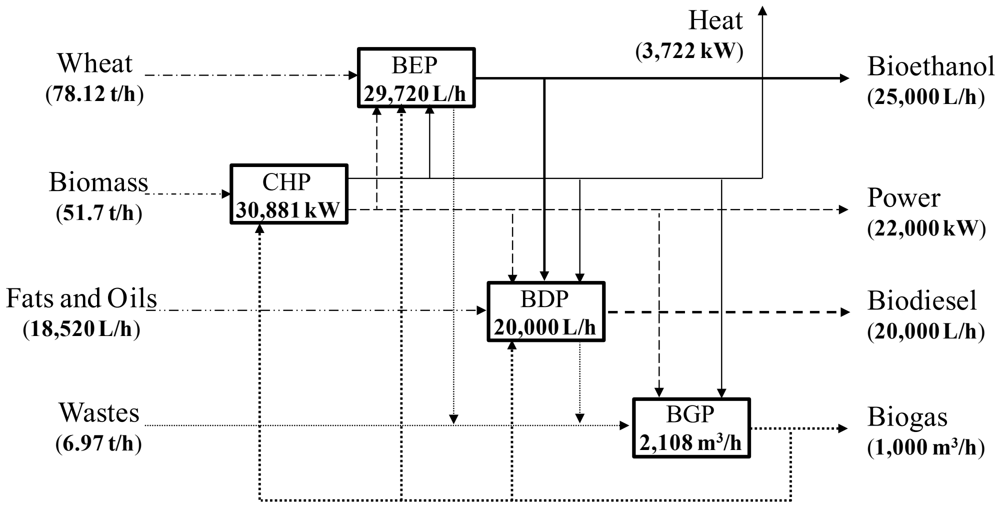


Figure 1. Bioenergy park input and output flow diagram for the baseline state.

Table 1. Process Data for the Baseline State of the Bioenergy Park.

Stream	CHP Plant	BEP	BDP	BGP	Final Output
Power, kW	1	-0.2590	-0.0132	-0.4354	22,000
Bioethanol, L/h	0	1	-0.236	0	25,000
Biodiesel, L/h	0	0	1	0	20,000
Biogas, m^3/h	-0.02963	-0.003810	-0.004	1	1000

Table 2. Baseline State and Capacity Change of Component Plants in the Bioenergy Park.

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4
CHP Plant, kW	30,881	-5.0%	-1.3%	-0.3%	-0.2%
Bioethanol Plant, L/h	29,720	0.0%	-5.0%	-0.8%	0.0%
Biodiesel Plant, L/h	20,000	0.0%	0.0%	-5.0%	0.0%
Biogas Plant, m^3/h	2,108	-2.2%	-0.8%	-0.3%	-5.0%

A 5% reduction in plant capacity is assumed in the criticality index calculation. In each scenario, it is assumed that a specific component plant will only affect the final output of a particular product stream while maintaining the final output of the other streams. Equation (2) is used to solve the final output of each product stream in each scenario. The fractional change in plant capacity of the four scenarios is presented in Table 2. Equation (3) is then used to determine the fractional change in the directly affected product streams and Equation (4) is used to solve the criticality index of the component plants. The fractional change in the final output of the product streams are as follows: 0.069 for Power, 0.059 for Bioethanol, 0.05 for Biodiesel, and 0.104 for Biogas. The CHP plant, bioethanol plant, biodiesel plant, and biogas plant have criticality indices of 1.4, 1.2, 1.0, and 2.1 respectively. The component plants in the symbiotic network can then be ranked based on this index to determine which plant will require risk mitigation measures. Thus, the Biodiesel plant ranks fourth, the Bioethanol plants ranks third, and the CHP plants ranks second. In this work, the biogas plant has the highest value of criticality index and ranks first. This means that a reduction in biogas plant capacity results to a greater net loss in biogas output compared to other product streams.

4. Conclusions

A criticality index for component plants in a symbiotic bioenergy network was developed in this work. This index provides a measure of how vital each plant is relative to the operations of the entire system. It is defined as the ratio of the fractional change in the final output of the directly affected product stream based on the baseline state to the fractional change in the capacity of the corresponding component plant. Thus, the component plants can be ranked based on this proposed index to determine the most critical player in the network. The significance of this criticality index was demonstrated using a symbiotic bioenergy park as case study.

Acknowledgements

The authors acknowledge the support from the Philippine Department of Science and Technology via the Engineering Research and Development for Technology Scholarship Program.

References

[1] Martin M, Eklund M. Improving the environmental performance of biofuels with industrial symbiosis. *Biomass and Bioenergy* 2011;**35**:1747-55

[2] Chertow MR. Industrial Symbiosis: literature and taxonomy. *Annual Review of Energy and the Environment* 2000;**25**:331-37

[3] Zeng Y, Xiao R, Li X. Vulnerability analysis of symbiosis networks of industrial ecology parks. *Procedia Computer Science* 2013;**17**:965–72

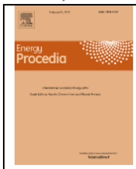
[4] Kasivisvanathan H, Barilea IDU, Ng DKS, Tan RR. Optimal operational adjustment in multi-functional energy systems in response to process inoperability. *Applied Energy* 2013;**102**:492-00

[5] Duchin F. Industrial input-output analysis: Implications for industrial ecology. *Proc. Natl. Acad. Sci. USA* 1992;**89**:851-55

[6] Khanna V, Bakshi BR. Modeling the risks to complex industrial networks due to loss of natural capital. *IEEE International Symposium on Sustainable Systems and Technology* 2009; doi:10.1109/ISSST.2009.5156771

[7] Haimes YY, Jiang P. Leontief-based model of risk in complex interconnected infrastructures. *Journal of Infrastructure Systems* 2001;**7**:1-12

[8] Tan RR, Lam HL, Kasivisvanathan H, Ng DKS, Foo DDCY, Kamal M, et al. An algebraic approach to identifying bottlenecks in linear process models of multifunctional energy systems. *Theoretical Foundations of Chemical Engineering* 2012;**46**:642-50



Biography

Michael Francis D. Benjamin is currently a faculty member of the Chemical Engineering Department at the University of Santo Tomas in Manila, Philippines, and a Ph.D. Chemical Engineering student at De La Salle University, Manila, Philippines.